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Tunneling in heterogeneous rock masses with a block-in-matrix fabric

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ABSTRACT

Heterogeneous rock masses composed of strong rock blocks embedded in a weaker matrix belong to complex formations and are often referred to as bimrocks (block-in-matrix-rocks). Due to the high spatial, dimensional, geo-hydrological and lithological variability of such rock bodies, a common geotechnical engineering design practice is not to consider the presence of the blocks and assign the strength and deformability properties of the weaker matrix to the whole rock mass. However, over the last decades, several case histories and many relevant studies on bimrocks have demonstrated that neglecting the presence of the blocks can produce wrong forecasts, which often lead to serious technical problems and severe economic repercussions during the construction of engineering works on and in these complex formations.

The aim of this study is to investigate the stability of a deep circular tunnel excavated in a heterogeneous rock mass with a chaotic block-in-matrix fabric. In order to determine how the presence of rock inclusions may influence the overall behavior of the bimrock during the excavation, different Volumetric Block Proportions (VBPs) are used. To take the inherent spatial and dimensional variability of the blocks into account, many heterogeneous tunnel configurations are generated for each VBP considered by means of a stochastic approach. The analyses are performed using the Finite Element code RS2.

Moreover, in order to highlight potential inaccuracies caused by neglecting the presence of the blocks at the design stage, simplified approaches commonly used by geopractitioners, which assume bimrocks to be homogeneous equivalent geomaterials, are also applied by way of comparison.

KEYWORDS

Bimrocks, heterogeneous rock masses, tunneling, stochastic approach, FEM

1 INTRODUCTION

Bimrocks (block-in-matrix rocks) are complex, heterogeneous and often chaotic formations composed of competent rock blocks embedded in a matrix of finer and often sheared texture.¹⁻³

38 These geomaterials are widespread all over the world and encompass many geological rock units
39 such as melanges, agglomerates, conglomerates, breccias, fault rocks, etc..⁴⁻¹⁰ Due to the high
40 spatial, dimensional, geo-hydrological and lithological variability that characterize these rock
41 formations, the determination of their geomechanical properties is extraordinary problematic.¹¹⁻
42¹⁵ As a consequence, geotechnical engineers often plan their work neglecting the contribution of
43 blocks to the overall bimrock strength, choosing instead to design on the basis of the strength and
44 deformation properties of the weaker matrix only.^{2,16-18} However, as documented by several case
45 histories reported in the literature, such a simplified assumption can cause mischaracterizations
46 and wrong forecasts in the planning phases, leading to unexpected technical problems and delays
47 during the construction of engineering works on and in these complex formations.^{6,18-24}
48 Many research studies (laboratory and in situ tests, as well as numerical simulations) conducted
49 on this topic over the last decades have demonstrated that the behavior of bimrocks is largely
50 controlled by the size, shape, position, orientation and content of the blocks within the rock mass.
51 Laboratory tests have been performed by many authors on artificial bimrock specimens since
52 1994 to study the effects that block proportion and orientation have on the mechanical properties
53 of melanges.^{3,7,17,25-28} A few authors have also performed laboratory tests on real bimrock
54 specimens^{13,29,30} developing empirical approaches for the determination of their uniaxial
55 compressive strength and elastic modulus on the basis of the Volumetric Block Proportion (VBP).
56 These works have also revealed that blocks strongly influence the mechanical behavior of such
57 geomaterials if rock inclusions represent at least 20% of the total rock mass volume.
58 Moreover, in situ large scale direct shear tests have been carried out on different rock-soil
59 mixtures.^{5,31-33} These experiments have demonstrated that the strength parameters of a bimrock
60 are correlated to the VBP and that the presence of rock inclusions controls the development,
61 position and shape of failure surfaces.
62 Numerical simulations of laboratory tests on bimrocks with different VBPs have also been carried
63 out in order to study the mechanical behavior and failure pattern of these complex
64 geomaterials.^{10,34-38}
65 Furthermore, slope stability in heterogeneous formations has been investigated using both
66 deterministic and stochastic approaches.^{22,39-43} The main findings of these studies show that
67 safety factors increase with increasing VBP and that both the position and shape of failure surfaces
68 are strongly affected by the presence of the blocks.
69 The aim of this paper was to examine how the presence of rock inclusions can affect the stability
70 conditions of a bimrock during the excavation of a deep tunnel. In fact, to the authors' knowledge,
71 very few works have been carried out on this specific topic. In particular, a theoretical circular
72 tunnel was supposed to be excavated in a chaotic melange with variable VBPs. In order to
73 generate the numerical models, a specific Matlab routine, performing Monte Carlo simulations,
74 was implemented. The Matlab code generates elliptical blocks with random dimensions,
75 orientations and positions within the rock mass, according to specific statistical rules and given

76 rock contents. For each VBP considered, ten extractions (generating ten bimrock configurations)
77 and, hence, ten numerical simulations were carried out by means of Finite Element (FE) analyses,
78 to achieve a statistical validity of the results.

79 A VBP value of 0%, corresponding to a matrix-only model, was also analyzed in order to
80 investigate potential inaccuracies and inconsistencies arising from the simplified design approach
81 (which neglects the presence of rock inclusions at the design stage), which is often used by
82 geopractitioners.

83 Furthermore, two empirical strength criteria available in the literature were applied to compare
84 the results obtained using homogeneous models rather than a (more complex) heterogeneous one.

85

86 2 TUNNELING IN BIMROCKS

87 Excavating tunnels in difficult ground conditions (e.g. soft rocks, fault zones, mixed face
88 conditions, weathered or fractured rock masses, and many others) often leads to critical situations
89 such as wall/face instabilities, breakdown or failure of excavation machine components,
90 uncontrolled over-excavations, heavy loading on preliminary supports and final linings, water
91 inflows, cutter wears, boreability problems, etc..^{21,44-47} All these aspects may have a significant
92 impact on the logistic of tunnel constructions, with serious delays, safety problems and cost
93 increments.⁴⁸⁻⁵⁰

94 To date, to the authors' knowledge, not much research on tunneling in bimrocks has been carried
95 out.

96 A 2D Finite Element analysis has been performed by Pustow⁵¹ in order to investigate stress
97 redistributions and critical states during the "Spital" underground excavation (Austrian Alps) in
98 a melange with lenticular inclusions (i.e. tectonic melange). The author analyzed seven models,
99 five with a single block of variable dimension and position (from 7 m to 70 m) arranged at the
100 left sidewall of the tunnel, a matrix supported melange and a block supported melange. The results
101 show that the blocks are characterized by stress concentrations if in contact with each other, and
102 that block dimensions affect their distribution. Moreover, due to the increase of the rock mass
103 strength, the radial displacements around the tunnel decrease. Experiences gained during the
104 construction of the Spital and Steinhaus tunnels are also reported in other papers.^{21,45}

105 Moritz et al. (2004) have illustrated their experience with a shallow tunnel excavated in
106 heterogeneous formations located in the Eastern Alps of Austria. One of these geologic units is a
107 tectonic melange with a block-in-matrix fabric. The material is characterized by smaller blocks
108 embedded in a soft and weathered matrix, consisting of cataclastic phyllites. The authors highlight
109 how important is a continuous updating of observed ground conditions during underground
110 excavations (observational method) in these complex geomaterials. In particular, the evaluation
111 and interpretation of 3D displacement monitoring data can be used for on-site short term
112 prediction of the rock mass structure and quality.⁵⁰

113 Adam et al. (2014) worked on the city bypass tunnel of Waidhofen an der Ybbs (Austria), where
114 difficult ground conditions were encountered due to the presence of a tectonic melange and
115 creeping slopes. In particular, various tunneling methods were applied on the basis of the
116 overburden and rock mass properties. Moreover, a sophisticated monitoring system was installed
117 in order to face the complex geological and morphological situation.⁴⁷ The analyses have been
118 performed on an equivalent homogeneous material applying the empirical approach proposed in
119 1994 by Lindquist³ and reported in Eq. (1):

$$\tau_p = c_{matrix}(1 - VBP) + \sigma \tan(\varphi_{matrix} + \Delta\varphi_{matrix}(VBP)) \quad (1)$$

121 where τ_p is the equivalent mass shear strength, c_{matrix} is the cohesion of the matrix (assumed to
122 decrease with increasing VBP), φ_{matrix} is the internal friction angle of the matrix and $\Delta\varphi_{matrix}(VBP)$
123 is the increase of the internal friction angle, assumed by Lindquist to be, above 25% VBP, equal
124 to 3° for every VBP increase of 10%.

125 Marinos et al. (2014) proposed a new Geological Strength Index (GSI) chart for heterogeneous
126 rock masses such as flysch and a range of geotechnical parameters for 11 flysch types, according
127 to their siltstone-sandstone proportion and tectonic disturbance. Moreover, the authors provided
128 specific recommendations for temporary support measures in underground excavations through
129 the different flysch types, based on their geotechnical behavior and critical failure mechanism.⁵²

130 Colmenares et al. (2017) worked on the Bogota-Villavicencio road, a very important connection
131 between the Colombian capital and the eastern plains. Difficult ground conditions, characterized
132 by a highly heterogeneous geology, favored the occurrence of multiple landslides over time.
133 These instabilities have required many interventions since 1995, including underground
134 excavations. Tunnel designs were mainly developed using the methodology proposed by the
135 Austrian Society of Geomechanics. The approaches proposed by Medley and Lindquist⁵³ were
136 followed to determine the ground properties and select the constitutive model, on the basis of rock
137 contents and laboratory test results carried out on the matrix. Numerical simulations were also
138 performed to design and back analyze the excavation processes during construction works.⁵⁴

139 All these studies concerning tunneling in complex formations with a block-in-matrix fabric
140 highlight that appropriate ground investigations and numerical analyses must be performed,
141 adequate construction and support methods must be used and appropriate monitoring systems are
142 required in order to allow a safe tunnel construction.

144 3 2D SIMULTATIONS OF TUNNEL EXCAVATION IN BIMROCKS

145 The aim of this study was to investigate how different block proportions may affect the
146 stability of a deep circular tunnel excavated in a heterogeneous rock mass with a chaotic block-
147 in-matrix fabric, by means of numerical simulations. To this purpose, these simulations were
148 carried out using different VBPs. In particular, 25%, 40%, 55% and 70% VBPs were examined.
149 To take the innate spatial and dimensional variability of the blocks into account, the stochastic

150 approach proposed by Napoli et al. (2018)^{41,42} was applied. In particular, a Matlab routine was
151 appositely implemented to randomly generate and locate elliptical blocks within the rock mass.
152 For each VBP considered, ten tunnel configurations were created with the Matlab code.

153 A 0% VBP configuration was also analyzed in order to evaluate potential inaccuracies that
154 geopractitioners could make when designing on the basis of the strength and deformation
155 properties of the matrix only.

156 Moreover, numerical simulations were also carried out following both the Lindquist (1994a) and
157 Kalender et al. (2014) empirical approaches. These approaches assume bimrocks to be equivalent
158 homogeneous and isotropic materials.

159 Altogether, the excavation of more than forty bimrock tunnels was simulated using the Finite
160 Element Method (FEM) in two-dimensional conditions.

161 The matrix and blocks mechanical parameters that were used in the analyses are reported in Table
162 1. Both materials present sufficient mechanical contrast ($E_{\text{block}}/E_{\text{matrix}} > 2$ and $\tan\phi_{\text{block}}/\tan\phi_{\text{matrix}} >$
163 2), as suggested by many authors.^{1,7,17,24,35,55-57} They were assumed to obey the Mohr-Coulomb
164 failure criterion and to follow an elastic-perfectly plastic behavior.

166 3.1 GENERATION OF TUNNEL CONFIGURATIONS

167 In order to model the spatial and dimensional variability inherent in bimrocks, a specific
168 Matlab routine, performing Monte Carlo simulations, was appositely implemented. The code
169 generates elliptical rock inclusions with eccentricity equal to 0.5, and random dimensions and
170 orientations. It also locates the blocks randomly within the rock mass, according to given
171 geometric boundaries, VBPs and statistical block size distribution parameters.³⁶ The size of the
172 blocks is strictly dependent on the characteristic engineering dimension, L_c , set equal to 10 m,
173 corresponding to the diameter of the tunnel.^{2,58} To maximize the code performance, blocks
174 placing is made from the largest to the smallest one.⁴¹ Moreover, the Matlab code verifies that
175 blocks do not interpenetrate each other, otherwise it would have no physical meaning. To this
176 reason, it was set a minimum distance between two blocks equal to 5 cm.

177 For the four VBPs considered (25%, 40%, 55% and 70% VBP), ten bimrock configurations were
178 created.

179 The main Matlab code output consists of a text file containing, for each tunnel configuration, a
180 list of the coordinates of both the center and the vertex of the semi-major axis and the length of
181 the semi-minor axis of each ellipse, representing a block.

182 An example of the final geometry obtained with this process is shown in Fig. 1.

184 3.2 FINITE ELEMENT ANALYSES

185 Finite Element (FE) analyses were conducted using the 2D FEM software RS2 (vers. 9.0)
186 from Rocscience. Six-node triangular elements were used to mesh the models.

187 Sensitivity analyses were carried out to evaluate the influence of external boundaries, geometry
188 and mesh density. In particular, with the purpose of avoiding boundary effects, bimrock models
189 were modified to include an outer layer $5L_c$ long (i.e. 50 m) on each side (Fig. 2). An elastic
190 behavior and the same mechanical properties of the matrix were assigned to this extended part of
191 the geometry of the bimrock models. To guarantee a high mesh quality, a non-uniform mesh size,
192 denser near the blocks, was created (Fig. 3). Moreover, local mesh refinements were adopted
193 where necessary.

194 A constant and isotropic field stress was assigned to the models, assuming an in situ state of stress
195 (p_0) depending on the VBP. In particular, an increasing equivalent unit weight was assigned to
196 the rock mass for higher block contents, obtaining p_0 values ranging from 1.65 MPa to 1.74 MPa.
197 Furthermore, 12 excavation stages (the first in elastic conditions and without the presence of the
198 tunnel) were simulated to reproduce the progressive underground excavation. The convergence-
199 confinement method was used, which simulates the ongoing excavation by means of a progressive
200 reduction of the stresses acting on each node located on the tunnel boundary. Each stage
201 corresponds to a stress reduction of $10\%p_0$. An elastic perfectly plastic behavior was adopted for
202 both the matrix and blocks belonging to the bimrock model, assigning the mechanical
203 characteristics reported in Table 1.

204 As previously mentioned, an only-matrix model and ten bimrock configurations for each VBP
205 considered, i.e. forty heterogeneous tunnel models, were simulated. Displacements and
206 characteristic curves, stresses and yielded zones were analyzed in detail with particular reference
207 to points R.S., C. and L.S. of the crown and the sidewalls, respectively (Fig. 3), under no support
208 pressure either at the wall or at the face.

209 The results obtained indicate that for increasing VBP values displacements undergo an evident
210 reduction with respect to those of the matrix (Fig. 4 and Fig. 5).

211 For the left sidewall (point L.S.), for example, the average maximum radial displacements
212 (provided by the 10 simulations analyzed for each VBP considered) are 0.94 m, 0.87m, 0.44m
213 and 0.14 m for the 25%, 40%, 55% and 70% VBP models, respectively, against the 1.57 m
214 obtained with the matrix-only model (Table 2).

215 According to previous literature findings, the presence of blocks with a low VBP provides
216 relatively little geomechanical advantage compared to the matrix-only model.^{1,3} However, the
217 position, orientation, dimension and number of the blocks located near the tunnel strongly affects
218 the results. As shown in Fig. 4 and Fig. 5, the radial displacements at the crown and sidewalls
219 provided by the ten 25% VBP configurations presented the greatest data dispersion. On the other
220 hand, for increasing rock contents a remarkable less data scattering is registered (Fig. 4, Fig. 6
221 and Table 3). In fact, the standard deviations of the radial displacements registered at the crown
222 (point C.) and sidewalls (points R.S. and L.S.) provided by the 10 tunnel models analyzed for
223 each VBP are greatly reduced passing from 25% to 70% VBP bimrock models, e.g. the right
224 sidewall standard deviations are reduced from 0.26 (for 25% VBP configurations) to 0.07 (for

225 70% VBP configurations). This outcome can be ascribed to the different block positions,
226 dimensions and orientations as well as to block-poor zones of variable extension and location
227 (within bimrock models having the same VBP), more evident for lower VBPs, which influence
228 the rock mass behavior.

229 Moreover, Fig. 6 shows the variability and the non-uniformity of the radial displacements around
230 the tunnel for the ten configurations analyzed for each VBP, due to the random location of the
231 blocks within the rock mass. This also induces non-uniform stresses that have to be taken into
232 account when designing the tunnel lining.

233 In order to better visualize the effects of the excavation on the different rock masses (from the 0%
234 to the 70% VBPs), Fig. 7 and Fig. 9 illustrate the increasing in displacements with decreasing
235 internal pressure (i.e. advancing tunnel face) on both tunnel sidewalls and crown. In particular,
236 for each VBP considered, a variation band of radial displacements provided by the 10 tunnel
237 models is shown. The upper and lower limits of each band were obtained by adding and
238 subtracting from the average radial displacement the associated standard deviation. From these
239 figures it is clear that blocks play a key role in the stability of the tunnels. For higher VBP values,
240 in fact, the displacement bands depart from the red curve, which represents the displacements
241 associated with the matrix-only model. Moreover, the greater the VBP the less thick the band,
242 which indicates that a less data scattering is provided by the 10 models analyzed.

243 Stresses and yielded zones are also affected by the presence of the rock inclusions, especially by
244 those located close to the tunnel (Fig. 10, Fig. 11, Fig. 12), and are considerably different from
245 the uniform matrix-only results. Fig. 10 and Fig. 11 show that the blocks are characterized by
246 stress concentrations, the distribution of which greatly depends on the block dimensions. In
247 particular, higher stresses are observed in the blocks of greater dimension located in the vicinity
248 of the tunnel, as well as at the block-matrix contacts. This result is in line with previous research.⁵¹
249 As illustrated in Fig. 12, the extension of the yielded zones greatly reduces for higher VBPs. It
250 also varies from model to model with the same rock content, according to block sizes, locations
251 and orientations. It is worth pointing out that plasticity occurs within the matrix only. As a
252 consequence, the length of the plastic radius varies around the tunnel depending on the presence
253 of the blocks.

254 As shown above, different stress distributions, yielded zones and displacements are provided by
255 each tunnel configuration, even by those having the same VBP. This variability suggests the
256 necessity of performing numerical simulations in these complex geomaterials according to a
257 stochastic approach, which may avoid mistakes resulting from either only considering a
258 homogeneous rock mass or just performing a deterministic analysis. In fact, since real block
259 positions and dimensions cannot be predicted, a stochastic approach may be useful at the design
260 stage to predict possible unfavorable conditions during the excavation works. Moreover, when
261 the observational method is implemented during the construction process, the displacement
262 measured at a given point should be compared and ought to be within the computed range of

263 displacements obtained with the stochastic approach. However, since many uncertainties exist
 264 when dealing with bimrocks, an observational method together with appropriate and continuous
 265 monitoring systems must always be used.

266

267 3.3 APPLICATION OF THE EMPIRICAL STRENGTH CRITERIA

268 In order to compare the results reported in Section 3.2 with those provided using equivalent
 269 homogeneous models, the empirical strength criteria proposed by Lindquist³ and Kalender et al.
 270⁷ were applied to the tunnel models considered.

271 The equivalent bimrock cohesion and internal friction angle were evaluated, for all the previously
 272 analyzed VBP values, according to Eq. (1) for the Lindquist criterion and according to the
 273 following Eqs. (2-4) for the Kalender criterion (see Table 4). The other input parameters (E , ν , γ)
 274 were assumed to be equal to those assigned to the matrix and reported in Table 1.

$$275 \varphi_{bimrock} = \varphi_{matrix} \left[1 + \frac{1000 \left[\frac{\tan(\alpha)}{\tan(\varphi_{matrix})} - 1 \right]}{1000 + 5 \left(\frac{100 - VBP}{15} \right)} \left(\frac{VBP}{VBP + 1} \right) \right] \quad (2)$$

$$276 UCS_{bimrock} = \left[\left(A - A^{\frac{VBP}{100}} \right) / (A - 1) \right] UCS_{matrix}, \quad 0,1 \leq A \leq 500 \quad (3)$$

$$277 c_{bimrock} = UCS_{bimrock} [1 - \sin(\varphi_{bimrock})] / [2 \cos(\varphi_{bimrock})] \quad (4)$$

278 where α is the angle of repose of blocks, assumed as equal to 45° , UCS is the material uniaxial
 279 compressive strength and A is a parameter that can be defined according to both the adhesion
 280 strength between the matrix and blocks and parameter α , determined as equal to 4.

281 As shown in Fig. 13 and Fig. 15, the strength criterion proposed by Lindquist (1994a) yields
 282 conservative results, especially for lower VBP values. For the 25% and 40% VBP models, results
 283 are remarkably similar to those provided by the matrix-only model, although more conservative.
 284 In particular, the maximum radial displacements are 2.09 m and 1.69 m, respectively, greater than
 285 1.57 m obtained with the matrix-only model.

286 Better conditions are provided by 55% and 70% VBP models, where the maximum radial
 287 displacements are 1.37 m and 1.25 m, respectively.

288 The results obtained using the Kalender et al. (2014) empirical approach are less conservative
 289 than both the matrix-only and the Lindquist models (Fig. 14). In fact, the maximum radial
 290 displacements are 1.39 m, 1.06 m, 0.94 and 1.03 m for 25%, 40%, 55% and 70% VBPs,
 291 respectively. However, especially for VBPs greater than 40%, they differ considerably from the
 292 results provided by the heterogeneous models, leading to an erroneous estimation of the
 293 mechanical response of the bimrock to the excavation process (Fig. 15).

294 Moreover, it is worth pointing out that the use of both the empirical criteria implies neglecting
 295 the presence of blocks and analyzing a homogeneous material. This assumption results in
 296 unrealistic final outcomes, since uniform stress distributions, plastic zones and radial
 297 displacements are obtained. However, the non uniformity shown by the heterogeneous models

cannot be neglected, because it takes primary importance in the design of the tunnel lining. Hence, these simplified approaches seem to be acceptable if used in predesign stages only.

CONCLUSIONS

This work investigates the effects of the VBP on the stability of deep circular tunnels excavated in a complex formation with a block-in-matrix fabric and the reliability of designing on the basis of the strength of the matrix only, as often happens in practice.

More than 40 2D numerical analyses were performed on different bimrock models, using the FEM code RS2 from Rocscience. Block dimensions, orientations and positions within the rock masses were randomly obtained using a stochastic approach performing numerical Monte Carlo simulations. For each VBP considered, ten bimrock configurations were generated with the aim of taking spatial and dimensional variability of rock inclusions into account. Furthermore, the empirical strength models proposed by Lindquist (1994a) and Kalender et al. (2014), which assume these geomaterials to be equivalent homogeneous, continuous and isotropic rock masses, were applied by way of comparison.

The results obtained provided the following principal findings.

The use of a matrix-only model, neglecting the presence of blocks, leads to homogeneous yielded zones and stress distributions which are unrealistic, since they are strongly affected by the presence of the rock inclusions (e.g. yielded zones develop tortuously within the matrix), as demonstrated in previous research. Moreover, severe overestimations of both displacements and plastic zone extension and shape are provided. This overestimation becomes steadily more evident as the VBP increases. Therefore, the choice of ignoring the contribution of blocks to the overall bimrock strength, choosing instead to design using the strength and deformation properties of the weaker matrix only, appears to be inappropriate and over conservative (i.e. uneconomical).

When analyzing bimrocks using the strength criterion proposed by Lindquist (1994a), the analyses provide conservative results, remarkably similar to those of the 0% VBP model. In particular, for a low VBP, some points around the tunnel showed even higher convergences than the matrix-only model. More stable conditions are provided by 55% and 70% VBP models, although these are considerably different from those yielded by the heterogeneous tunnel models. The results obtained using the Kalender et al. (2014) empirical approach are less conservative than both the matrix-only and the Lindquist models. However, especially for VBP greater than 40%, they too provide results which differ considerably from those of the heterogeneous configurations.

All the same, it is worth pointing out that the use of these two empirical criteria implies neglecting the presence of blocks and analyzing an equivalent homogeneous material. This assumption results in many uncertainties in the final outcomes, as highlighted by previous findings^{41,42}, since they underestimate the mechanical behavior of the bimrock. Hence, they seem to be acceptable if used in predesign stages only. Moreover, it is worth mentioning that ignoring the presence of the

336 blocks can also lead to delays and unexpected technical problems during many engineering works,
337 with possible significant economic repercussions.^{6,18-24}

338 On the other hand, the simulations carried out for the heterogeneous models demonstrate that
339 blocks play a key role in the behavior of bimrocks during underground excavation processes.
340 Shear stresses, displacements and plastic zones are in fact strongly affected by the presence of
341 blocks located near the tunnel, as well as by their dimensions. Moreover, yielded zones develop
342 tortuously within the matrix according to previous literature findings. The FEM analyses on these
343 models demonstrate that even for a VBP equal to 25% the presence of blocks may induce quite
344 significant variations in the strength of the rock mass. This variation becomes more evident for
345 greater VBP values. However, very different results are yielded by the ten models with lower
346 VBP values. This behavior can be ascribed to the different block positions and variably extended
347 block-poor zones near the tunnel (within bimrock models having the same VBP), which influence
348 stresses and shear strain concentrations and, consequently, the stability of the rock mass. The non
349 uniformity of stresses and displacements around the tunnel can strongly influence the state of
350 stress induced in the tunnel lining, which affects its design. This problem is not taken into account
351 with the equivalent homogeneous models.

352 There is compelling evidence that deterministic analyses cannot take these particular
353 characteristics into account. Conversely, a stochastic approach seems to be more reliable to study
354 these complex formations, since it makes it possible to predict possible unfavorable conditions
355 during the excavation works, perceiving the variability in the results. The assumptions made
356 during the design phase and the numerical analysis results both have to be verified during
357 construction. In particular, when applying the observational method, actual ground displacements
358 at a given point should be compared and ought to be within the computed range of displacements
359 obtained with the stochastic approach. However, since many uncertainties exist when dealing
360 with bimrocks, an observational method together with appropriate and continuous monitoring
361 systems must always be used.

362 It is worth pointing out that the main limitation of this study is that plane strain conditions were
363 assumed for both the matrix and blocks by analyzing 2D bimrock configurations instead of more
364 realistic 3D models.

365 Hence, in order to investigate the implications that this assumption could have produced on the
366 results found in this paper, a future work will be to carry out statistical analyses of 3D tunnel
367 stability in the same bimrock formations and compare the results.

368

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371

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